

A Conceptual Framework for Understanding Faster-Than-Light Neutrinos

Eric Sakk¹ and Aradhya P. Kumar²

¹Department of Computer Science
eric.sakk@morgan.edu

²Department of Physics
Morgan State University, Baltimore, MD, 21251
aradhya.kumar@morgan.edu

Abstract

Recent experiments have led to the production of neutrinos with transit times indicating the appearance of traveling faster than the speed of light. In this paper, we present a conceptual framework to understand how faster-than-light events involving neutrinos (as indicated by time-of-flight) might occur. We propose that observations of this kind do not violate the special theory of relativity; instead, they only help to provide evidence in support of the general theory of relativity at quantum scales. Given the relativistic effects of the neutrino on its local spacetime environment, the measured time-of-flight at the macroscopic level is attributable to a decrease in the effective path length traversed by the neutrino. Specifically, along preferred directions, we show that the Kerr metric allows for the compression of spacetime; hence, the decreased path length hypothesis is plausible. Furthermore, when the motion of the neutrino is along the preferred direction for spacetime compression, the Kerr metric also predicts strong frame dragging effects near the Planck length. In the region where strong frame dragging occurs, we propose that the microscopic explanation for the path length compression is due to the formation of 'micro-wormholes' near the Planck length.

1 Introduction

A recent set of high energy experiments and associated measurements appear to indicate that neutrinos can travel faster than the speed of light [6, 11]. Such observations are reminiscent of and potentially consistent with reports of neutrinos detected from supernova events [7, 5, 4, 10]. The scientific community as a whole is on very solid ground in its unwillingness to entertain the idea that particles can be energized to exceed the speed of light. Clearly, either the observations are incorrect or there exists a sensible explanation that could lead to a deeper understanding of neutrino behavior. In the event that the experimental results are correct, it is sensible to seek after a more accurate description of particle behavior that would not violate the theory of relativity.

The purpose of this work is to offer a possible resolution that necessarily requires describing the interaction of the neutrino with its spacetime surroundings in a manner consistent with the general theory of relativity. This setting is ideal for considering only the gravitational effect of an uncharged particle possessing nonzero angular momentum. We therefore propose that the particle behavior can be approximated by considering effects derivable directly from the Kerr metric; namely, path length compression and frame dragging. Given the possibility of a spacetime compression, the measured time-of-flight at the macroscopic level is attributable to a decrease in the effective path length traversed due to neutrino-spacetime interactions at high energies.

The 'faster-than-light' claim has arisen in many contexts. A common example comes from tunneling experiments with photons [13, 8]. Quantum mechanics does not provide a complete

description detailing how the photon arises on the other side of a barrier; however, it is clear that the decreased optical path length leads to the macroscopic illusion of faster-than-light group velocity. While the mechanism we present in this work is due to gravitational effects, the principle of a decreased path length is the same. For this work, in addition to the spacetime compression observable from a macroscopic rest frame, we further propose that the microscopic explanation lies in frame dragging effects also predicted by the Kerr metric. Specifically, we hypothesize the formation of 'micro-wormholes' to account for tunneling behavior at microscopic scales near the Planck length.

Section 2 describes the path length compression effect as derived from existing experimental data. Section 3 then derives conditions where the Kerr metric predicts spacetime compression along preferred directions of motion. Section 4 then briefly investigates why other particles within the standard model have not exhibited similar behavior. Section 5 continues this discussion by analyzing frame dragging effects for charged versus uncharged leptons. It is then pointed out that, for the Kerr metric at scales near the Planck length, strong frame dragging occurs along the same directions where spacetime compression is demonstrated in Section 3. Finally, in addition to discussing various implications of the neutrino behavior, Section 6 raises the idea of 'micro-wormhole' formation to account for particle tunneling behavior at microscopic scales near the Planck length.

2 Path Length Analysis

The traversal time t_ν of the neutrino over a length ℓ has recently been measured to be less than that of a photon t_p [6, 11],

$$t_\nu = \frac{\ell}{\beta c} < \frac{\ell}{c} = t_p \quad (1)$$

(where $\beta > 1$), leading to the perception of faster-than-light neutrino velocity βc . Viewed in this light, it is possible to arrive at the incorrect conclusion that special relativity is being violated. Instead, we describe a general relativistic formalism that characterizes the effect of the neutrino on its spacetime surroundings. Specifically, as measured from the reference frame of an observer at rest, we propose that the effective path length decreases to a value of $\ell' \equiv \gamma_\nu \ell$ where $\gamma_\nu < 1$ is the neutrino path length compression factor. Furthermore, according to special relativity, the actual neutrino velocity as observed from a rest frame must be $v_\nu = \eta_\nu c$ where $\eta_\nu < 1$. Hence, the traversal time is more accurately described as

$$t_\nu = \frac{\ell'}{v_\nu} = \frac{\gamma_\nu \ell}{\eta_\nu c} = \frac{\ell}{\left(\frac{\eta_\nu}{\gamma_\nu}\right)c} \quad (2)$$

Comparing this result with Equation (1), imposes the condition

$$\beta = \frac{\eta_\nu}{\gamma_\nu} > 1 \Rightarrow \eta_\nu > \gamma_\nu. \quad (3)$$

From [6, 11], the assumed velocity $v_a = \beta c$ in Equation (1) can be related to the experimentally observed values:

$$\frac{v_a - c}{c} = \frac{\beta c - c}{c} = \beta - 1 = 10^{-5}. \quad (4)$$

However, given Equation (3), we propose that the condition

$$\frac{\eta_\nu}{\gamma_\nu} - 1 = 10^{-5} \quad (5)$$

more accurately characterizes the observed neutrino effect. Since η_ν is a knowable quantity (e.g. $\eta_\nu \approx .999995$), we can isolate the value of the neutrino path length compression factor γ_ν in order to describe the general relativistic effects on spacetime leading to the value

$$\gamma_\nu = \frac{\eta_\nu}{1 + 10^{-5}}. \quad (6)$$

As another example, consider data recorded from Supernova 1987A [7] where $\ell \approx 168,000$ light years and neutrinos reached detectors on earth approximately 3 hours ($\approx 10^4$ sec) before the supernova was visible. Under these circumstances, using the above formulation, the arrival time difference can be characterized as

$$\Delta t = t_p - t_\nu = \frac{\ell}{c} - \frac{\ell}{\beta c} = \frac{\ell}{c} \left(1 - \frac{1}{\beta}\right). \quad (7)$$

Assuming $(v_a - c)/c \approx 10^{-9}$ for neutrinos ejected from the supernova, we arrive at value of $\beta = 1 + 10^{-9}$. According to Equation (7),

$$\Delta t = \frac{(1.68 \times 10^5)(9.64 \times 10^{15})}{3 \times 10^8} \left(1 - \frac{1}{\beta}\right) = 5 \times 10^3 \text{ s} \quad (8)$$

which approaches the observed arrival time difference between the neutrinos and photons.

3 Neutrino-Spacetime Interactions at High Energy

3.1 Kerr Metric

The mean free path length for the neutrino is enormous; hence, the path length compression effect is cumulative and observable only at high energies. In addition, since the neutrino is a chargeless lepton, we hypothesize that the compression effect is likely due to gravitational interactions at extremely small scales. To this end, we propose the Kerr metric [9, 12] as a starting point for understanding the behavior of a gravitational mass possessing angular momentum interacting with its spacetime surroundings. Specifically, the Kerr metric for a mass M with angular momentum J can be written using spherical coordinates (r, θ, ϕ) as:

$$c^2 d\tau^2 = \left(1 - \frac{r_s r}{\rho^2}\right) c^2 dt^2 - \frac{\rho^2}{\Delta} dr^2 - \rho^2 d\theta^2 - \left(r^2 + \alpha^2 + \frac{r_s r \alpha^2}{\rho^2} \sin^2 \theta\right) \sin^2 \theta d\phi^2 + \frac{2r_s r \alpha \sin^2 \theta}{\rho^2} c dt d\phi \quad (9)$$

where

$$r_s = \frac{2GM}{c^2} \quad (10)$$

is the Schwarzschild radius which defines the event horizon for an uncharged blackhole with zero angular momentum. In addition, the following quantities:

$$\begin{aligned}\alpha &= \frac{J}{Mc} \\ \rho^2 &= r^2 + \alpha^2 \cos^2 \theta \\ \Delta &= r^2 - r_s r + \alpha^2\end{aligned}\tag{11}$$

provide insight regarding the behavior of the metric components. For instance, for a muon neutrino, appropriate parameter values correspond to $|J| = \hbar/2$ and $M \approx 170 \text{ keV}/c^2$. Under these circumstances, $r_s = 4.48 \times 10^{-58} \text{ m}$ and $\alpha = 5.81 \times 10^{-13} \text{ m}$.

3.2 Spacetime Compression

For a non-rotating body, using spherical coordinates, the dr^2 term in the Schwarzschild metric contains the factor $g_{rr} = -(1 - \frac{r_s}{r})^{-1}$. Consider two concentric spheres in the geometry defined by the Schwarzschild metric. Along the radial direction, with time held constant, an observer at rest would measure a distance of $(1 - \frac{r_s}{r})^{-1/2} dr$. Hence, as the radial distance decreases from $r = \infty$ to $r = r_s$, flat spacetime becomes 'stretched' by the factor $(1 - \frac{r_s}{r})^{-1/2}$. For the case of the Kerr metric, this effect appears to be quite different due to the introduction of the angular momentum term α in Equation (11). Under these circumstances, the Kerr metric in Equation (9) yields the term $g_{rr} = -\frac{\rho^2}{\Delta}$ (which reduces to the Schwarzschild term when $\alpha = 0$). For the Schwarzschild case $|g_{rr}| > 1$ as long as $r > r_s$. However, this is not necessarily the case for the Kerr metric. Observe, a spacetime compression can take place whenever the condition $\frac{\rho^2}{\Delta} < 1$ is satisfied. Let us investigate how such a condition for spacetime compression might arise by considering Equation (11)

$$\begin{aligned}\rho^2 < \Delta &\Rightarrow r^2 + \alpha^2 \cos^2 \theta < r^2 - r_s r + \alpha^2 \\ &\Rightarrow \alpha^2 (1 - \cos^2 \theta) > r_s r\end{aligned}\tag{12}$$

and, hence, all values of r such that

$$r < \frac{\alpha^2 \sin^2 \theta}{r_s} \equiv r_C\tag{13}$$

will lead to a factor in g_{rr} such that spacetime is compressed. Given the parameter values from Section 3.1, it is clear that such a condition can be satisfied. In fact, when $0 < r < r_C$, it follows that $0 < \frac{\rho^2}{\Delta} < 1$. Clearly, for some values of θ , there will be no compression effect. For instance, if $\theta = 0$, then $r_C = 0$. On the other hand, given a neutrino ensemble, the effect should be observable for particles where $\theta \rightarrow \pi/2$.

Rigorously verifying such an effect necessarily requires more accurately describing the particle behavior at the quantum level. In this presentation, we temporarily circumvent this more rigorous path in order to present an approximate framework using the Kerr metric and investigating the feasibility of such a hypothesis. Let us consider the case of maximum compression where $\theta = \pi/2$. Observe, in rectangular coordinates (e.g. $\{x, y, z\}$) this corresponds to the spin vector \vec{J} aligned with the z -axis (see Figure 1). Assuming the direction of motion to be in the $x - y$ plane, and, without loss of generality, along the x -axis, spacetime compression would take place along the direction of motion. The obvious goal then is to relate the radial compression factor to γ_ν in Equation (6).

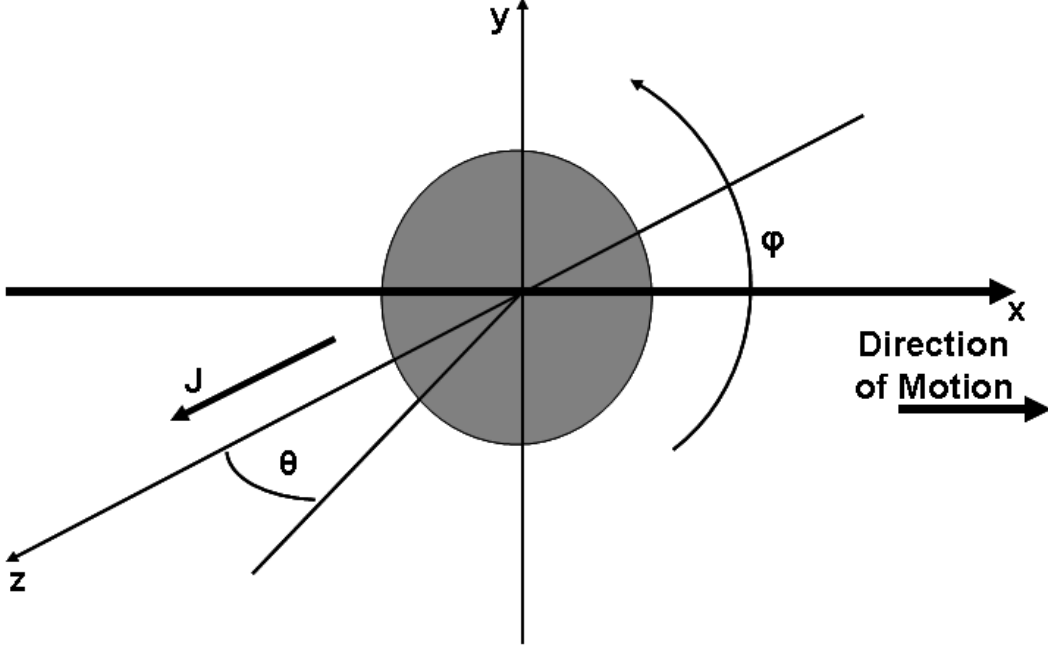


Figure 1: Particle in spherical coordinates where the spin vector is aligned with the z -axis and direction of motion is along the x -axis.

Then, it must also follow that

$$\sqrt{\frac{\rho^2}{\Delta}}|_{\theta=\frac{\pi}{2}} = \sqrt{\frac{r^2}{r^2 - r_s r + \alpha^2}} = \gamma_\nu, \quad (14)$$

or, in other words,

$$\gamma_\nu = \sqrt{\frac{\rho^2}{\Delta}}|_{\theta=\frac{\pi}{2}} = \sqrt{\frac{1}{1 + \frac{\alpha^2 - r_s r}{r^2}}}, \quad (15)$$

As in the previous section, assuming $\eta_\nu \approx .999995$, Equations (6) and (15) then tell us that

$$\frac{\alpha^2 - r_s r}{r^2} \approx 10^{-4}. \quad (16)$$

Therefore, given the parameters listed in Section 3.1, we arrive at the following approximate result:

$$r^* \approx \sqrt{10^4 \alpha^2} \approx 10^{-11} \text{ m} \quad (17)$$

where r^* represents the effective neutrino radius that generates the experimentally observed compression factor γ_ν .

4 Evaluation within the Context of the Standard Model

We next consider particle categories consistent with those observed within the context of the standard model in order to understand why the observation of the compression effect has been limited to

the neutrino. As stated above, the main reason is most likely due to the fact that the neutrino is an uncharged lepton with an enormous mean free path length. Many particles in the standard model can immediately be eliminated based simply upon the short lifetimes. Particles with long lifetimes generally have mean free paths much shorter than the neutrino. In addition, charged particles will necessarily interact with the electromagnetic field.

4.1 Uncharged Particles with Nonzero Spin

In the case of particles having mass, the candidate metric to apply is the Kerr metric [9, 12] which is applicable to uncharged bodies with mass possessing nonzero angular momentum.

- **Neutrons:** The neutron might also be a candidate for observing the compression effect. If so, the implications regarding the formation of dark matter at the time of the big bang would have to be investigated (see Discussion section below). On the other hand, larger neutron mass and size might also lead to factors preventing it. If Equations (12) and (13) are applied to the neutron, $r_* \approx 10^{-14}$ might prevent the effect given the size of the neutron. In addition, the quark structure of the neutron may be a factor in precluding the use of the Kerr metric as an approximation to quantum gravitational effects.
- **Photons:** Photons are massless; hence, a spacetime compression effect would not be possible and the Kerr metric analysis would be applicable in this case.
- **W Bosons:** The lifetime for these particles are much too short to observe such an effect.

4.2 Charged Particles with Nonzero Spin

For particles with charge, the electromagnetic force is assumed to overwhelm the gravitational effect. The theory of general relativity allows for geodesics to be affected by charge. Under these circumstances, the Kerr-Newman metric is useful for describing massive charged bodies with nonzero angular momentum.

- **Electrons:** Given the lifetime of the electron, it seems that the electron could be a candidate for the spacetime compression effect; however, it is likely that electromagnetic interactions could prevent the electron from establishing a long enough path to observe the effect. Furthermore, as explained below, there may be general relativistic reasons due to frame dragging that inhibit the effect as well.
- **Muons and Tauons:** The lifetime for these particles are much too short to observe such an effect.
- **Z Boson:** The lifetime for this particle is much too short to observe such an effect.
- **Protons:** In addition to mass, size and quark issues similar to that of the neutron mentioned above, electromagnetic interactions due to the proton charge may prevent observation of the effect.

4.2.1 Kerr-Newman Metric

It has been proposed that the Kerr-Newman metric is useful for describing the behavior of the electron [1, 2]. The Kerr-Newman metric for a charged mass M with charge Q and angular momentum J can be written using spherical coordinates (r, θ, ϕ) as:

$$c^2 d\tau^2 = -\left(\frac{dr^2}{\Delta} + d\theta^2\right)\rho^2 + (cdt - \alpha \sin^2 \theta d\phi)^2 \frac{\Delta}{\rho^2} - ((r^2 + \alpha^2)d\phi - \alpha cdt)^2 \frac{\sin^2 \theta}{\rho^2} \quad (18)$$

where, once again,

$$r_s = \frac{2GM}{c^2} \quad (19)$$

is the Schwarzschild radius. Furthermore, introducing the charge Q leads to the metric parameters:

$$\begin{aligned} \alpha &= \frac{J}{Mc} \\ \rho^2 &= r^2 + \alpha^2 \cos^2 \theta \\ \Delta &= r^2 - r_s r + \alpha^2 + r_Q^2 \\ r_Q^2 &= \frac{Q^2 G}{4\pi\epsilon_0 c^4}. \end{aligned} \quad (20)$$

Plugging in parameters leads to $r_Q^2 = 1.89 \times 10^{-72}$.

It will also be useful to express the Kerr-Newman metric as follows:

$$c^2 d\tau^2 = (g_{tt} - \frac{g_{t\phi}^2}{g_{\phi\phi}})dt^2 + g_{rr}dr^2 + g_{\theta\theta}d\theta^2 + g_{\phi\phi}(d\phi + \frac{g_{t\phi}}{g_{\phi\phi}}dt)^2 \quad (21)$$

where

$$\begin{aligned} g_{rr} &= -\frac{\rho^2}{\Delta} \\ g_{\theta\theta} &= -\rho^2 \\ g_{\phi\phi} &= -(r^2 + \alpha^2 + \frac{(r_s r - r_Q^2)\alpha^2}{\rho^2} \sin^2 \theta) \sin^2 \theta \\ g_{t\phi} &= \frac{(r_s r - r_Q^2)\alpha \sin^2 \theta}{\rho^2} c \\ g_{tt} &= (1 - \frac{(r_s r - r_Q^2)}{\rho^2}) c^2 \end{aligned} \quad (22)$$

As $Q \rightarrow 0$, $r_Q \rightarrow 0$ and the above equations reduce to those of the Kerr metric. Assuming $Q \neq 0$, Equations (12) and (13) can be rederived using $-\frac{\rho^2}{\Delta}$ for the Kerr-Newman metric. Under these circumstances, the compression condition becomes

$$r < \frac{(\alpha^2 + r_Q^2) \sin^2 \theta}{r_s} \equiv r_{QC}. \quad (23)$$

Since the r_Q^2 term is small with respect to α^2 , one might arrive at a conclusion similar to that for the Kerr metric; however, we point out an issue we believe sheds further light on the compression effect.

5 Frame Dragging

Using the Kerr-Newman metric, frame dragging effects can be computed from the quantity:

$$\Omega = -\frac{g_{t\phi}}{g_{\phi\phi}} = \frac{(r_s r - r_Q^2)\alpha c}{\rho^2(r^2 + \alpha^2) + (r_s r - r_Q^2)\alpha^2 \sin^2 \theta} \quad (24)$$

When $Q = 0$, this leads to $r_Q = 0$ and Equation (24) reduces to the frame dragging relationship typically encountered using the Kerr metric:

$$\Omega = \frac{r_s r \alpha c}{\rho^2(r^2 + \alpha^2) + r_s r \alpha^2 \sin^2 \theta} \quad (25)$$

As described in Section 3.2, with the spin vector aligned along the z -axis, spacetime rotation takes place in the ϕ direction (see Figure 1). Furthermore, along the direction for maximum compression outlined above, the limit of Equation (25) as $r \rightarrow 0$ along the direction of motion (where $\theta = \pi/2$) is $\Omega \rightarrow c/\alpha \approx 10^{20} s^{-1}$. Near the Planck length, $r \approx 10^{-35} m$ and $\Omega \approx .025 s^{-1}$, then Ω begins rapidly approaching its limit (see Figure 2). The behavior of Equation (25) is interesting in that $\Omega \rightarrow 0$ as $r \rightarrow 0$ from values of $\theta \neq \pi/2$. In addition, it is also true that values of Ω drop off rapidly as θ moves away from $\pi/2$. This behavior is illustrated in Figure 3 which shows contours of constant Ω in the $x - z$ plane near the value of r^* derived in Equation (17). As the angle diverges from $\theta = \pi/2$, Equation (25) behaves like r/k_1 as $r \rightarrow 0$ and k_2/r^3 as $r \rightarrow \infty$ (where k_1, k_2 are positive constants) with a single maximum between these two limits. Hence, for any angle, there will exist two contours yielding the same angular frequency. Near $\theta = \pi/2$, however, Ω behaves as in Figure 2 and values of Ω are substantially larger along the assumed direction of motion. Hence, Kerr metric-based frame dragging appears to give results consistent with the spacetime compression formulation presented above when motion is along the $\theta = \pi/2$ direction. We therefore propose that strong frame dragging at scales near the Planck length may serve as a potential mechanism for initiating the observed spacetime compression.

On the other hand, for the Kerr-Newman metric, an interesting effect arises that differs in behavior from the Kerr metric. In this instance, we see that when

$$r = \frac{r_Q^2}{r_s} = \frac{1}{2\pi\epsilon_0 c^2} \frac{Q^2}{M} \quad (26)$$

is applied in Equation (24), the direction of rotation reverses as $r < \frac{r_Q^2}{r_s}$ changes to $r > \frac{r_Q^2}{r_s}$. A similar conclusion has been published in [3]. Given the parameter values from Section 3.1, Equation (26) implies that at $r \approx 10^{-14} m \gg$ electron radius, the direction of rotation reverses. In addition, the g_{tt} term in the Kerr-Newman metric changes from a compression to an expansion. We hypothesize that this shift in the angular rotation about the spin axis (as in the previous section, assumed to be along the z -axis) due to electromagnetic interactions with spacetime may inhibit the compression effect (which requires $r^* \approx 10^{-11}$ for the electron mass).

6 Discussion

The goal of this work has been to present a conceptual framework for understanding the faster-than-light neutrinos in terms of a path length compression due to general relativistic effects. Given a

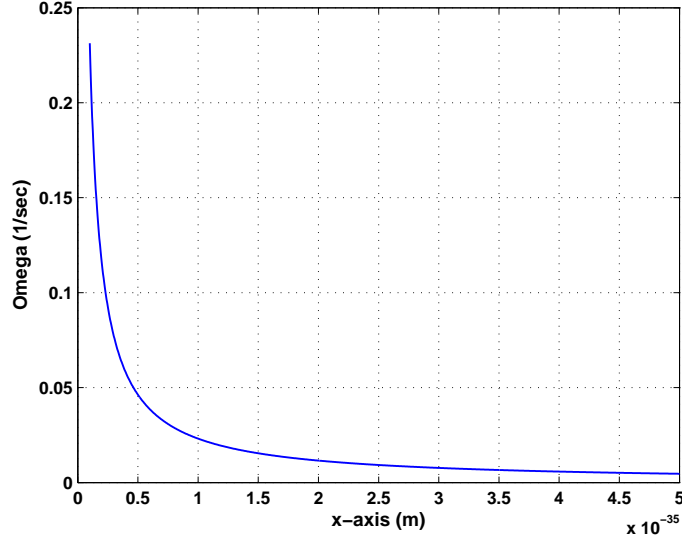


Figure 2: Equation (25) plotted along $\theta = \pi/2$ direction of motion.

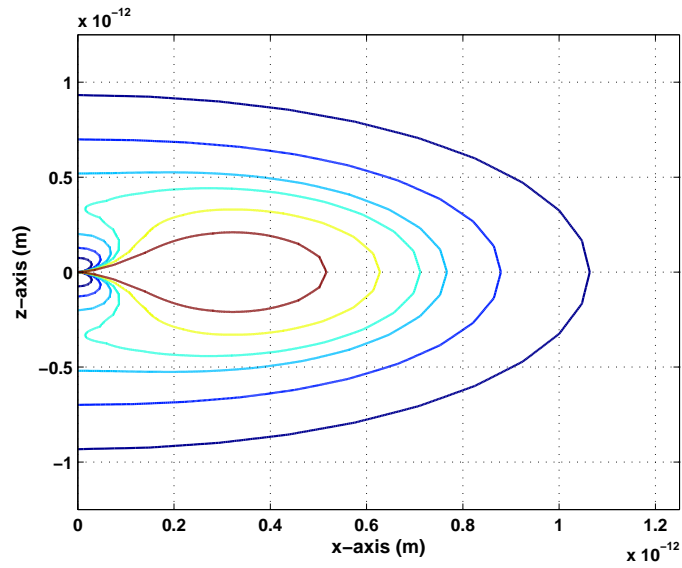


Figure 3: Contour plot of values where $\Omega = \text{constant}$ in Equation (25). Contours having the same color correspond to equal values of Ω .

century of experimental precedent, the unwillingness to give up c as a postulate of relativity is well-founded. Either the neutrino experiments are wrong or some effect needs to be further understood. Hence, we propose that general relativity at the quantum scale has the capacity to resolve the experiments if the neutrino effect is real. Under these circumstances, we view these results as an opportunity to help understand spacetime at scales approaching the Planck length. Specifically, we have proposed that strong frame dragging at scales near the Planck length may serve as a potential mechanism for initiating the observed spacetime compression.

One issue to be resolved is whether the neutrino should be modelled as a black hole or a singularity. Such questions can only be resolved with a more in depth formulation involving the Dirac equation. For the purposes of this work, we only require the above framework in order to derive approximate relationships. When the parameters described in this work are applied to the Kerr metric, conclusions similar to those described for the electron [1, 2] can be reached in that the neutrino could also be modelled as a singularity. For instance, one might seek to describe the event horizon by searching for values of r such that $\Delta \rightarrow 0$ in Equation (9) such that

$$r = \frac{r_s \pm \sqrt{r_s^2 - 4\alpha^2}}{2} \quad (27)$$

however, the parameters applied in this analysis would preclude the possibility of $\Delta \rightarrow 0$. On the other hand, a change from timelike to spacelike Kerr metric behavior can occur if

$$r = \frac{r_s \pm \sqrt{r_s^2 - 4\alpha^2 \cos^2 \theta}}{2} \quad (28)$$

Values where $\theta \rightarrow \pi/2$ would allow for this possibility for values where

$$\cos \theta < \frac{r_s}{2\alpha}. \quad (29)$$

This of course would place limits on the physical geometry of the particle such that $|\theta - \pi/2|$ is extremely small, possibly pointing to singular behavior [1, 2]. Observe that the geometric constraint $\theta \rightarrow \pi/2$ leading to singular behavior is consistent with the conditions for maximum compression presented in Section 3.2 and Section 5.

Given the approximate description presented above, the door has been opened for hypothesizing more accurate descriptions of neutrino-spacetime interactions. For instance, particle frame dragging effects near the Planck length could lead to the formation of 'micro-wormholes' through which the particle might travel. Since the Dirac equation does allow for spacetime tunneling effects, it may be interesting to formulate the field statistics of micro-wormholes. Hence, a quantum field description of spacetime compression might be formulated by addressing phase transitions where the spin frame dragging effect literally 'tears' into spacetime forming the micro-wormhole. Under these circumstances, rather than the compression appearing to be continuous at the macroscopic level, the effect would actually be statistical. In other words, similar to how a flat rock skips across a water surface, the particle skips through a series of micro-wormholes. In analogy to a sling-shot effect, the particle could possibly gain energy between skips leading to different path compression lengths.

The implications of the observations are manifold as they open up the possibility of developing techniques for engineering spacetime travel using neutrino-spacetime interactions. It may even be possible to amplify the effect by the presence of a local magnetic field designed to align the spins of a neutrino ensemble. Finally, if the spacetime path length compression effect is real, then the missing matter (e.g. dark matter, dark energy) problem might be resolvable by considering particles capable of compressing spacetime along their direction of motion. Clearly, after the big bang, an immense amount of gravitational neutrino mass (and possibly mass due to other particles with long enough lifetimes) travelling faster than photons would exist beyond the visible universe.

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